

# The Himalayan connection of the Middle Triassic brachiopod fauna from Socotra (Yemen)

MAURIZIO GAETANI†, MARCO BALINI, ALDA NICORA, MARTINO GIORGIONI & GIULIO PAVIA



The brachiopod fauna from the Middle Triassic beds of the Socotra Island, collected along the Ras Momi log, consists basically of four species, here described: *Nudirostralina mutabilis* (Stoliczka, 1866), *Lepismatina lilangensis* (Stoliczka, 1866), *Spirigerellina stoliczkai* (Bittner, 1899), *Adygella socotrana* sp. nov. Additional, very rare, species are *Koeveskallina* sp. and an undescribed very large dielasmaticid. This fauna is arranged in three assemblages, with different age. The older is represented by *Adygella socotrana* and dated as Bithynian according to the presence of the conodonts *Neogondolella regalis* and *Paragondolella bulgarica*. The middle one is the richest in specimens, with lumachelle of *Spirigerellina stoliczkai* and rare specimens of other species. Its age is Illyrian on the base of several species of Paragondolellids and Neogondolellids. The younger one contains rare very large dielasmaticid, *Nudirostralina mutabilis*, and *Spirigerellina stoliczkai*, which continues to be fairly abundant. The age of this assemblage is an indefinite Ladinian, due to the presence of *Budurovignathus* sp. This fauna is compared with a few specimens from Himalaya (*G. lilangensis*, *S. stoliczkai*, and “*Dielasma*” *himalayanum*), which were collected from the sections of Muth (Spiti), Phugtal (Zanskar), and Tulong (South Tibet). The brachiopod fauna of Socotra has an obvious counterpart with the Himalayan fauna, indicating a strong connection during the Middle Triassic. Our palaeobiogeographic interpretation is that Socotra was a part of the Indian Plate fringe or lying nearby during the Triassic. In the latest Triassic–Jurassic it was detached from the Indian margin with the Gondwana fragmentation, and then with the subsequent opening of the Indian Ocean in the Late Cretaceous. Socotra remained attached to the Arabian Peninsula until the opening of the Gulf of Aden in the Miocene. This separated Socotra from the Arabian Peninsula and left it as the easternmost tip of the Somali Plateau. • Key words: palaeontology, palaeobiogeography, brachiopods, Triassic, Yemen, Himalaya.

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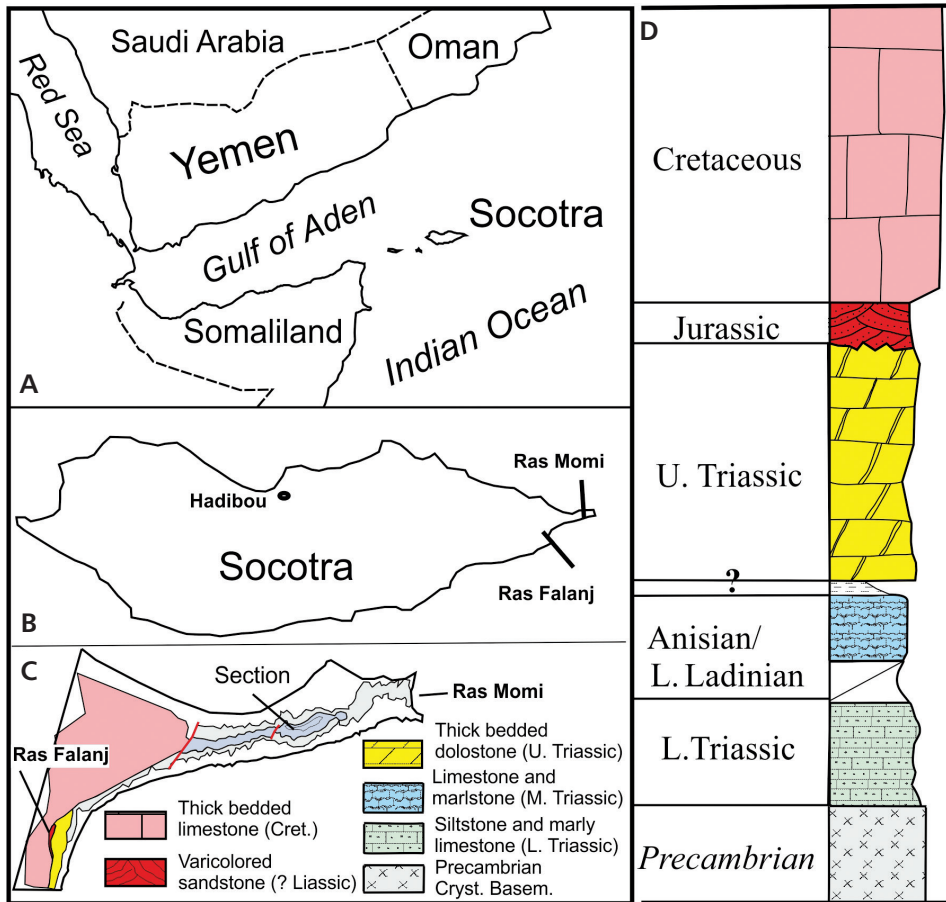
The Socotra Island (Yemen) is located out of the coast of the East African corner of Somalia, and presents the main geological features of South Oman (Dofhar Mountains) as well as the sedimentary cover of southern Yemen. However, the sedimentary succession of Socotra is of particular interest for the Triassic, as it represents the only location in the southern Middle East with outcropping marine facies of this period. These sediments were described for the first time by Samuel *et al.* (1997), within an oil prospecting study, but no detailed litho- and biostratigraphic study has been presented so far.

The general stratigraphy of the Triassic succession of Socotra was studied in the master thesis of Giorgioni (2006), and preliminary results were presented by Balini *et al.* (2008). Several brachiopod specimens were collected by M. Balini and G. Pavia in 2004 and by M. Gaetani,

M. Balini, and M. Giorgioni in 2005. Here we present the taxonomic description and palaeobiogeographic significance of the brachiopod fauna recovered in the Triassic succession of the Socotra Island, while detailed lithofacies, ammonoid, and conodont descriptions will be presented by M. Balini and A. Nicora in another work.

The aim of this paper is twofold: (i) illustrate the Triassic brachiopod assemblages of the Socotra Island and constrain their time of occurrence on the base of conodont biostratigraphic dating and (ii) discuss the affinities of the Triassic brachiopods from Socotra with the time equivalent fauna from Himalaya (India, Nepal, and Tibet), as well as their paleobiogeographic implications.

We show that the brachiopod assemblages found in Socotra have a strong affinity with those from Himalaya,



**Figure 1.** The island of Socotra (A), the position of studied section at the eastern tip of the island (B), geological sketch of the area Ras Momi-Ras Falanj (C), and a general scheme of the Mesozoic sedimentary succession in the eastern part of the island (D).

indicating a strong connection between the two provinces during the Triassic.

### Sedimentary succession of Socotra

The sedimentary succession of the Socotra Island lies non-conformably over a magmatic and metamorphic basement of late Precambrian age (Beydoun & Bichan 1969, Samuel *et al.* 1997). The Triassic portion outcrops only in the easternmost tip of the island and is best exposed in two locations: Ras Momi and Ras Falanj. The main lithostratigraphic units, shown in Fig. 1, consist of (from base to top):

(1) Conglomerates and sandstones, overlain by alternated shale, light grey skeletal carbonate, and marlstone. About 110m thick. Conodonts found the carbonate facies, with good to excellent state of preservation, indicate an age

ranging from Smithian (early Olenekian) to latest Anisian and Ladinian.

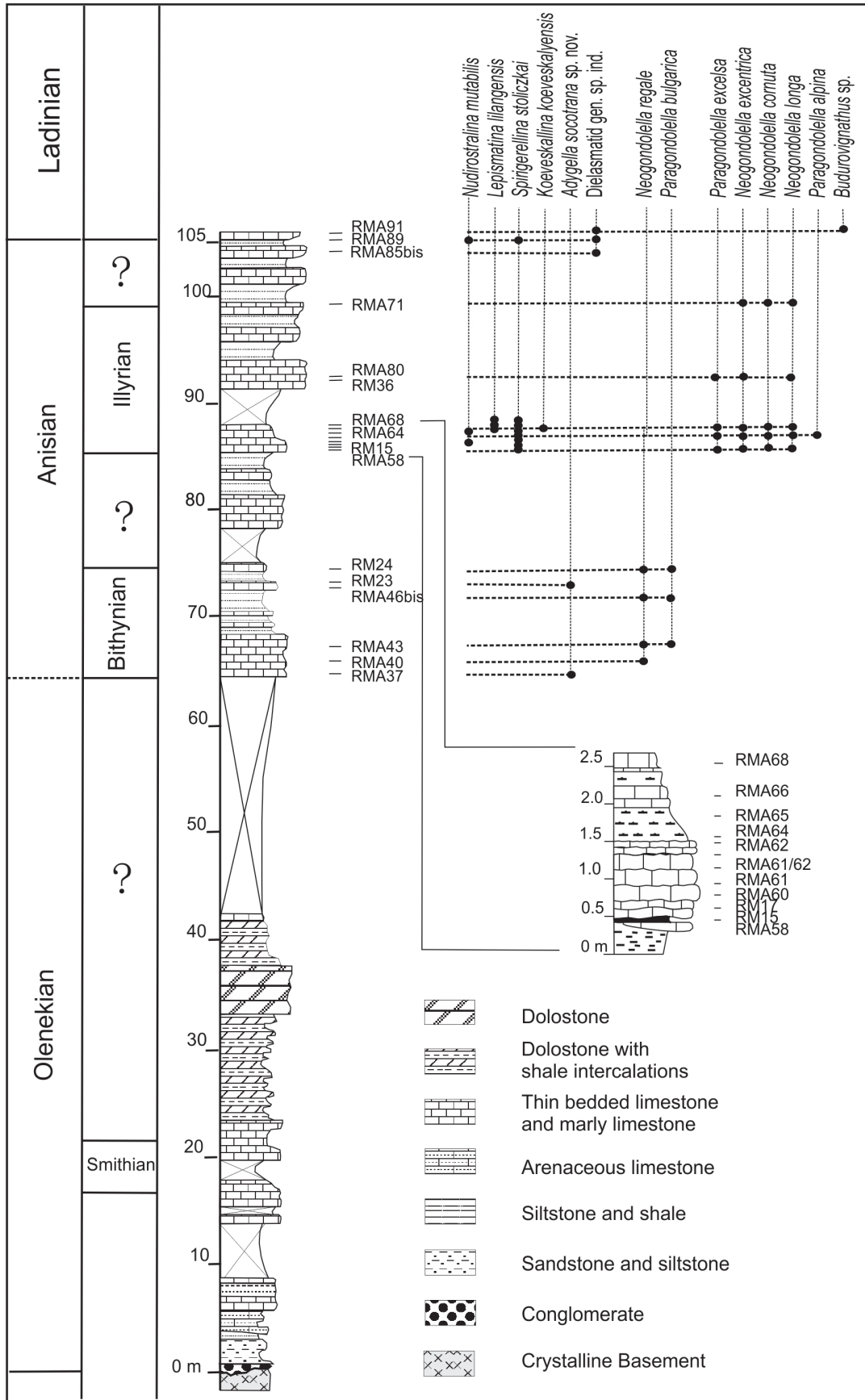
(2) Green shale, very poorly exposed, some tens of metres thick. Barren at the palynological analysis.

(3) Light dolostone, with beds 10 cm to 80 cm thick, arranged in m-thick bundles. The total thickness is about 100 m and the estimated age is Late Triassic, on the base of moulds of megalodontids.

(4) A major hiatus occurs above the Triassic units encompassing the uppermost part of the Triassic and lowermost of the Jurassic (Samuel *et al.* 1997).

(5) Cross-bedded coarse sandstones and fine conglomerates, often pink to reddish, a few tens of m thick. The age is estimated as Lower to Middle Jurassic, based on the affinity with the Karoo Formation or Adigrat Sandstone (Merla

**Figure 2.** The section of Ras Momi with the range of the studied brachiopods and the most significant conodonts species.



*et al.* 1979), and the overlying limestone layers with Toarcian microfauna (Banner *et al.* 1997).

(6) A major hiatus separates the former unit from the following, encompassing most part of the Jurassic and the lower part of the Lower Cretaceous (Samuel *et al.* 1997).

(7) Thick-bedded limestone and dolostone, forming the backbone of the island, several hundred metres thick. The age is estimated as mid Cretaceous (Barremian to Cenomanian; Morrison *et al.* 1997, Samuel *et al.* 1997).

(8) Cenozoic units are not present in the studied locations, but occur mainly in the western part of the island (Samuel *et al.* 1997).

Brachiopods fossils were found only in the lower part of the succession, which is the best preserved and exposed at Ras Momi, No brachiopods were collected at Ras Falanj, where mostly the upper part of the succession is exposed and the lithology is pervaded by intense dolomitization that overprinted all the primary features. Here we focus only on the section of Ras Momi, as it is the only that yielded well preserved brachiopods.

### Ras Momi section

The Ras Momi section is located in the easternmost tip of the Socotra Island, the Momi Peninsula. The outcrop lies along the upper part of a ridge that crosses the peninsula longitudinally, from east to west, and reaches a maximum altitude of 350m. The succession begins from the contact with the basement and continues almost undisturbed up to 104m. The bedding is exposed in a monoclinial series with orientation of 150°/18° (Fig. 2).

The lithostratigraphy, from the base to the top, is as follows:

Basement: Metasediments and amphibolites intruded by gabbros and acid intrusives. It is late Precambrian in age, according to Beydoun & Bichan (1969) and Samuel *et al.* (1997).

(1) A deepening upward sequence, about 10m thick, starting with a conglomerate layer, overlain by fine sandstone and platy limestone.

(2) About 40 m of thin-bedded platy limestone, progressively dolomitized and arranged in thickening upward cycles of 2 m to 5 m. Both the beds and cycle thicknesses increase gradually from the base to the top of this interval. The conodonts etched out yielded the Smithian age.

(3) About 60 cm of calcarenites with intraclasts and oncolites, locally cross-laminated, followed by more than 20 m of a barely cropping clayey marl.

(4) Bundles up to 5 m thick of thin-bedded nodular limestone, often bioturbated, alternating with grey-yellow marlstone. The entire interval is about 45 m thick, very rich in fossils, and dated with conodonts as Anisian (Bithynian to Illyrian). All the brachiopods presented in this work were collected from this interval.

The section ends at the summit of the ridge, where the succession is truncated by a normal fault.

### Triassic brachiopod fauna of Socotra

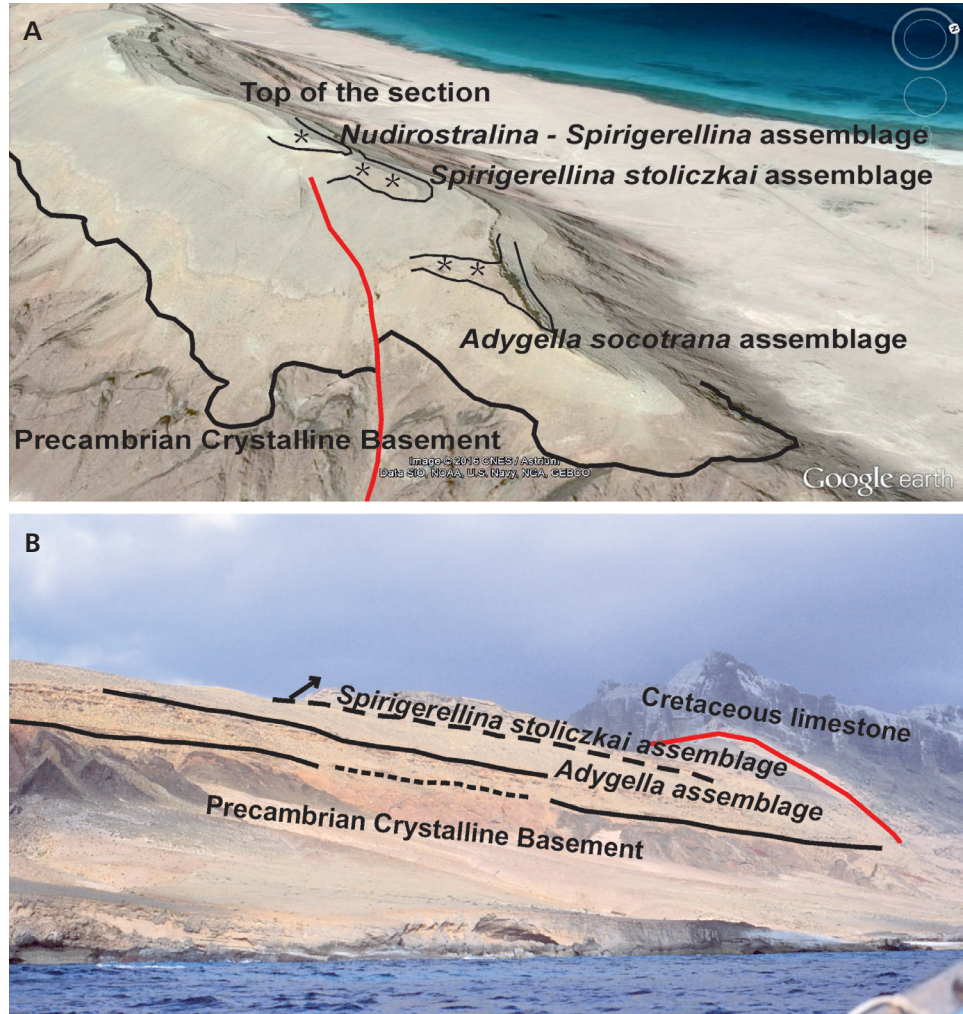
We identified three brachiopod assemblages, occurring from the base to the top of the studied interval (Fig. 3).

(1) *Adygella socotrana* Assemblage. It occurs between 68 m and 78 m from the base of the section, where a high frequency of *Adygella socotrana* sp. nov. has been observed (samples RMA37 and RM23, 68 specimens collected). The specimens are usually articulated and sparse within the marlstone and thin limestone beds. No other brachiopod species were found. Isolated fragments of crinoids are also present. This assemblage is accompanied by the conodonts *Neogondolella regalis* (sample RMA40), *Neogondolella regalis* and *Paragondolella bulgarica* (samples RMA43 to RMA46bis, and RM24); which suggest a Bithynian age (Nicora 1977).

(2) *Spirigerellina stoliczkai* lumachelle Assemblage. The interval between 88 m and 91 m from the base is the richest in brachiopod specimens, absolutely dominated by *Spirigerellina stoliczkai* (Bittner, 1899). Thousands of specimens were observed throughout the bed surfaces (RMA 58 to 68; Figs 2, 4). Brachiopod fossils occur mostly articulated, but also partly abraded and with rare bryozoan incrustations. They seem mechanically accumulated in a very shallow environment, locally forming shell lags. Sporadic partly silicified specimens may also occur (RMA 66). Locally intense burrowing was also observed.

Other accompanying brachiopod species consist of rare *Lepismatina lilangensis* (Bittner, 1899), very rare *Nudirostralina mutabilis* (Stoliczka, 1866) and a single valve of *Koeveskallina* cf. *koeveskalyensis* (Stur, 1865). The carbonate sandy bottom of this interval favoured the blossom of pedunculated brachiopods. *Lepismatina lilangensis* is often fragmented and disarticulated, because of its delicate shell. Ventral valves prevail. In the upper part of this interval, the specimen density decreases, as the sediments

**Figure 3.** A – oblique satellite imagery view of the Ras Momi section with the position of brachiopod assemblages (Google Earth image). • B – view of the section from the sea.



**Figure 4.** Lumachelle bed with *Spirigerellina stoliczkai* (Bittner, 1899). Bed RMA 64/65, Ras Momi section. The knife for scale is 9.4 cm long.



became muddier. Conodonts are also abundant, with *Paragondolella excelsa*, *P. liebermani*, *P. fueloepi*, *Neogondolella pseudobifurcata*, *N. excentrica*, and *N. balcanica*, which show the Illyrian age (Kozur & Mostler 1982, Kovács 1994, Nicora & Brack 1995, Brack *et al.* 2005).

This conodont/brachiopod assemblage continues upward, up to 103 m from the base, with less abundant occurrences. The conodonts *N. pseudobifurcata*, *N. excentrica*, *N. longa*, and *N. cornuta* continue up to the sample RMA71, still indicating an Illyrian age.

(3) *Nudirostralina mutabilis*-*Spirigerellina stoliczkai* Assemblage. The last faunal assemblage is restricted to the top of the section, where *Nudirostralina mutabilis* is frequent and *Spirigerellina stoliczkai* is still abundant, even though frequently fragmented. Very large dielasmatids, disarticulated and fragmented, occur here for the first time. A muddier bottom characterizes the environment of this last occurring assemblage. Specimens are sparse or form small pocket accumulations. The presence of *Budurovignathus* sp. suggests an Early Ladinian age (Kovács 1983, Krystyn 1983, Kozur *et al.* 1994, Nicora & Brack 1995, Brack *et al.* 2005).

In conclusion, the brachiopod faunas from the Ras Momi section encompass three major assemblages and span from the Bithynian (Early Anisian) to an indefinite Early Ladinian.

### Triassic successions of Himalaya

We compared the brachiopods found in Socotra with specimens from the Himalayan sections of Muth (Spiti), Phugtal (Zanskar), and Tulong (South Tibet). Brachiopods in these sections are always rare; therefore the comparison is based on few specimens.

Brachiopods from Muth, collected by M. Balini, were classified as *Spirigerellina stoliczkai*, *Lepismatina lilangensis*, and “*Dielasma*” *himalayanum*. All the specimens are from the bed E 37, near the top of the Himalayan Muschelkalk Member of the Mikin Formation. According to Krystyn *et al.* (2004), this bed represents the topmost part of the Bithynian.

Brachiopods collected by M. Gaetani from the Phugtal section, in Zanskar, are poorly preserved. However, it was possible to recognize *Nudirostralina* ex gr. *mutabilis*, *Koeveskallina* sp., *Lepismatina* sp., *Spirigerellina* sp., and “*Dielasma*” *himalayanum*. This assemblage was found in the basal beds of the upper member of the Tamba Kurkur Fm., considered of Pelsonian age (Nicora *et al.* 1985, Gaetani *et al.* 1986).

We also considered three specimens of “*Dielasma*” *himalayanum* (Bittner, 1899), kindly provided by E. Gar-

zanti and collected along the Tulong section in South Tibet. These specimens are from the 22 basal metres of the Qudenggongba Fm. (Garzanti *et al.* 1998, p. 148), which is dated as Bithynian-Pelsonian (E. Garzanti, personal communication).

### Systematic palaeontology

(M. Gaetani†)

*Repository.* – The material described here is housed in the Museo di Paleontologia dell’Università di Milano (MPUM). Samples have been coded with the label RM or RMA and are followed by the figure. The classification was performed according to the Treatise on Invertebrate Paleontology, part H, volumes 4 and 5 (Williams *et al.* 2002, 2006).

Phylum Brachiopoda Duméril, 1806

Subphylum Rhynchonelliformea Williams, Carlson, Brunton, Holmer & Popov, 1996

Class Rhynchonellata Williams, Carlson, Brunton, Holmer & Popov, 1996

Order Rhynchonellida Kuhn, 1949

Superfamily Rhynchonelloidea d’Orbigny, 1847

Family Rhynchonellidae d’Orbigny, 1847

### Genus *Nudirostralina* Yang & Xu, 1966

*Type species.* – *Nudirostralina subtrinodosi* Yang & Xu, 1966. Anisian of Qingyen, Gueiyang, SW China.

### *Nudirostralina mutabilis* (Stoliczka, 1866)

Figures 5A–F, 6

1866 *Rhynchonella mutabilis* Stoliczka, p. 40, pl. 3, figs 5–9.

1899 *Rhynchonella mutabilis* Stoliczka, 1866. – Bittner, p. 15, pl. 2, figs 11–13.

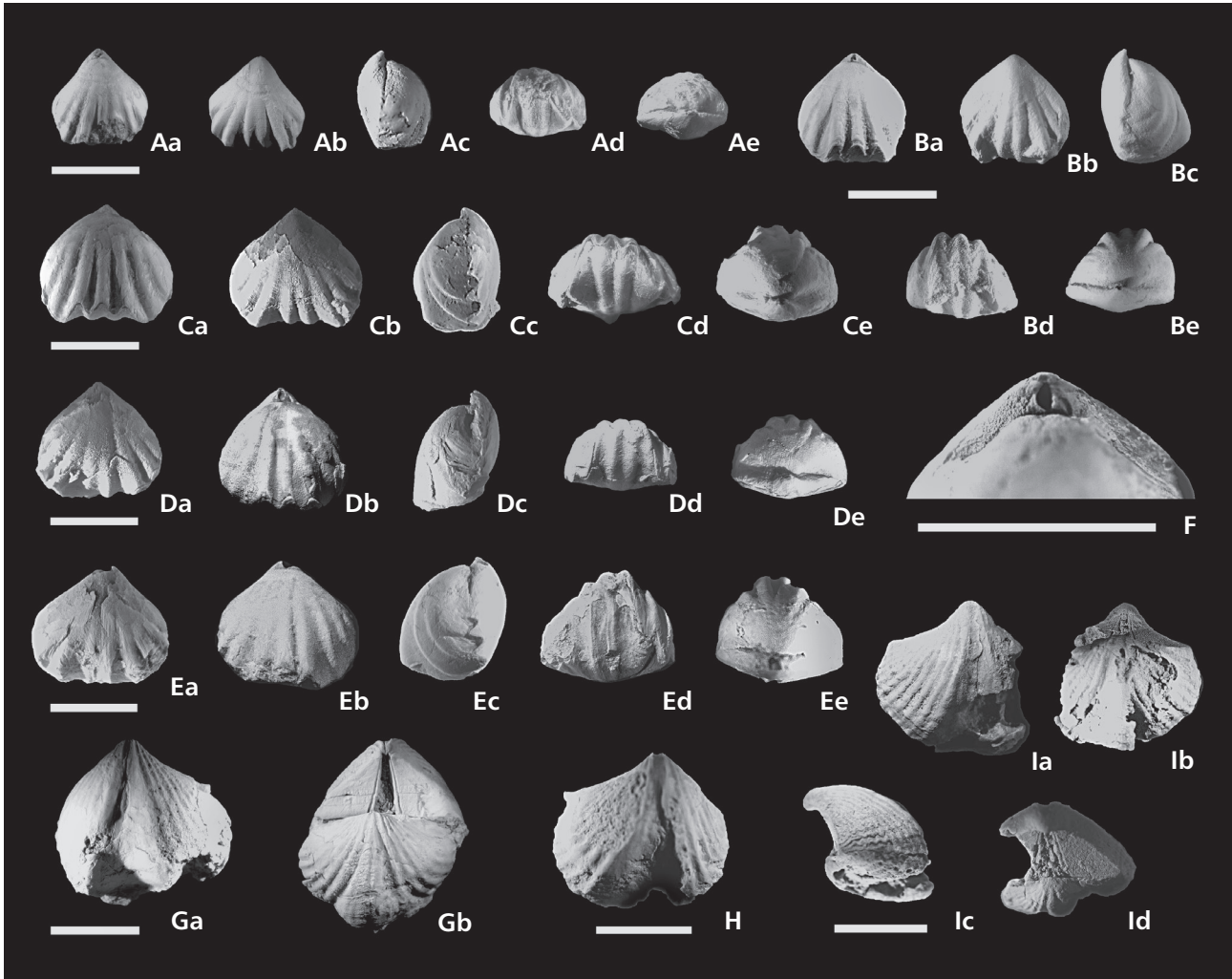
1907 *Rhynchonella mutabilis* Stoliczka, 1866. – Diener, p. 6.

? 1976 *Nudirostralina mutabilis* Stoliczka, 1866. – Jin & Sun in Jin *et al.*, p. 289, pl. 2, figs 6, 7.

*Material.* – Section Ras Momi: MPUM 11530, RMA 62 (1 spec.); MPUM 11531, RMA 65 (1 spec.); MPUM 11532 RMA 89 (24 spec.). Mostly articulated specimens.

*Description.* – Small to medium biconvex shell, with length similar or slightly exceeding width, uniplicate. Ventral valve with erect beak, foramen submesothyrid, small discrete deltidial plates. Sulcus originating at mid of the length, sharply delimited on the flanks.

Dorsal valve much thicker than the ventral, with thickness gradually growing up to the front. Fold present from the mid of the length.



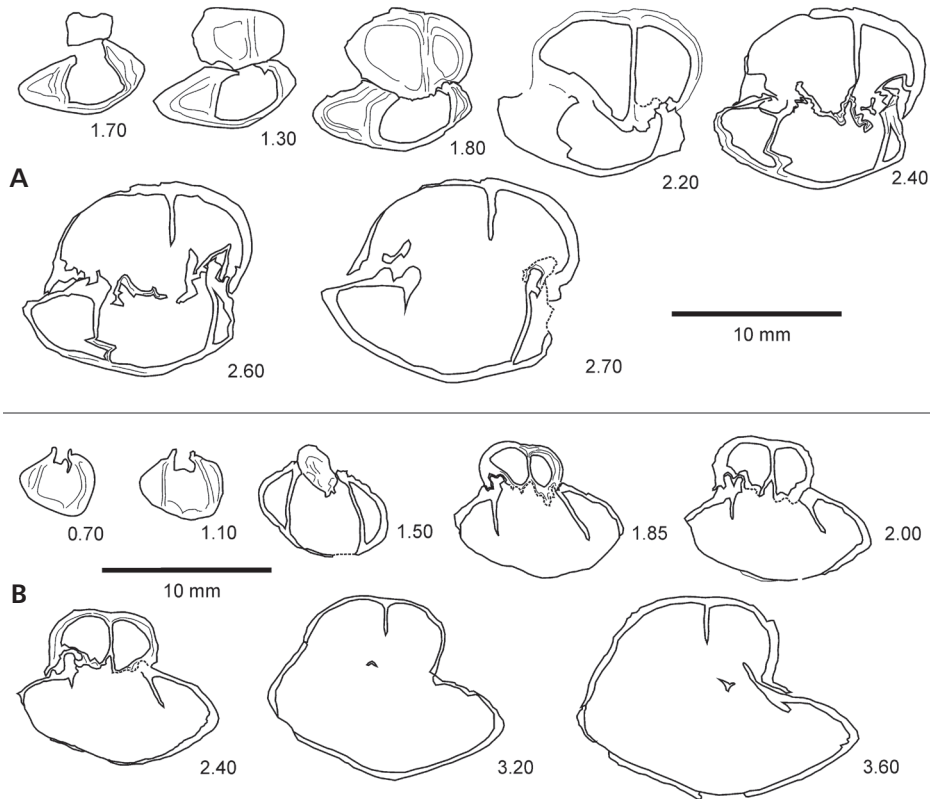
**Figure 5.** A–F – *Nudirostralina mutabilis* (Stoliczka, 1866). Scale bar = 1 cm; Aa–e – dorsal, ventral, lateral, anterior, and posterior views, respectively. Specimen RMA 89/6. MPUM11532; Ba–e – dorsal, ventral, lateral, anterior, and posterior views, respectively. Specimen RMA 89/3. MPUM11532; Ca–e – dorsal, ventral, lateral, anterior, and posterior views, respectively. Specimen RMA 89/5. MPUM11532; Da–e – dorsal, ventral, lateral, anterior, and posterior views, respectively. Specimen RMA 89/4. MPUM11532; Ea–e – dorsal, ventral, lateral, anterior, and posterior views, respectively. Specimen RMA 89/7. MPUM11532; F – detail of the umbo, with permesothryd foramen. Specimen RMA 89/4. MPUM11532. • G–I – *Lepismatina lilangensis* (Bittner, 1899); Ga, b – ventral and dorsal view, respectively. Specimen RMA 66/1. MPUM 11535; H – ventral view. Specimen RMA 66/2. MPUM 11535; Ia–d – ventral, dorsal, lateral, and posterior view, respectively. Specimen 64/6. MPUM 11533.

Ornaments made by simple angular costae, originating around mid of the length. The median costae have ratio 3/2 in 18 specimens, and 2/1 in 7 specimens. Dimensions (in mm) of the *Nudirostralina mutabilis* (Stoliczka, 1866) are listed in Table 1.

Internal features: The sectioned specimens are partly deformed and recrystallized. The quality of observation is rather poor. The ventral valve has dental plates, posteriorly markedly divergent, then more parallel and vertical. The dental plates bear bifid teeth and denticula. Lateral cavities open. Dorsal valve with deep septalium, high inner socket ridges and rather long median septum. Crural bases triangular, but poorly visible.

**Remarks.** – Without additional specimens from Himalaya at hand, it is difficult to assess the taxonomy of the rhynchonellids described by Bittner (1899). *Nudirostralina mutabilis* is described as similar to the smoother *Piarorhynchella trinodosi*. However, from the plate 2, figs 11–14 of Bittner (1899) the shell of *N. mutabilis* looks covered by costae originating at least at mid of the length. Also *P. trinodosi* of Diener (1907, pl. 1, fig. 1) has costae starting already before mid-length. In *P. trinodosi* from the Southern Alps, type-area of the species, the shell is smoother and costae start after the mid length (Gaetani 1969).

It is possible that, on the base of a larger collection, the three species, *griesbachi* (Bittner, 1899), *dieneri* (Bittner, 1899),



**Figure 6.** *Nudirostralina mutabilis* (Stoliczka, 1866). Serial sections. Distance from the umbo in mm. Scale bar = 1 cm; A – specimen RMA 65/1, MPUM 11531; B – specimen RMA 89/9, MPUM 11532.

and *mutabilis* will result as different ontogenic stages of the same species. In such a case, *mutabilis* will have priority. *Piarorhynchella trinodosi* (Bittner, 1890) sometimes reported also from Western Himalaya, has smoother shell, with costae originating more toward the front, with median costae dominated by the ratio 1/2 (Gaetani 1969). In *N. mutabilis* the ratio 2/3 prevails. The *N. mutabilis* figured by Jin and Sun in Jin *et al.* (1976) is poorly depicted and deformed.

**Occurrence.** – Socotra, brachiopod assemblages 2 and 3: Illyrian to earliest Ladinian. In Himalaya, *N. mutabilis* was described from the Himalayan Muschelkalk of Spiti, Bithynian/Pelsonian in age (Bittner 1899).

Order Spiriferida Waagen, 1883  
 Suborder Spiriferinida Ivanova, 1972  
 Superfamily Pennospiriferinoidea Dagys, 1972  
 Family Lepismatidae Xu & Liu, 1983

**Genus *Lepismatina* Wang, 1955**

*Type species.* – *Lepismatina hsui* Wang, 1955.

***Lepismatina lilangensis* (Stoliczka, 1866)**

Figure 5G–I

1866 *Spirifer (Spiriferina) lilangensis* Stoliczka, p. 38, pl. 3, fig. 4.

1899 *Spiriferina lilangensis* Stoliczka 1866. – Bittner, p. 20, pl. 4, fig. 2.

**Material.** – Ras Momi: MPUM 11533, RMA 64 (1 spec.); MPUM 11534 RMA 65 (2 spec.); MPUM 11535, RMA66 (2 spec.); MPUM 11536 RMA 68 (3 spec.). Muth, Spiti, India: MPUM 11537, E37. The specimens are mostly disarticulated and the ventral valve is more frequent. Only one specimen is articulated. Very fragile shell.

**Description.** – Small to medium sized spiriferinid, width about double of the length; maximum width at 1/3 of the length. Hinge with rounded ends, never mucronate. Ventral valve triangular in lateral outline, with high slightly apsacline interarea. Deep delthyrial grooves. Wide median sulcus, labiate at the front. Dorsal valve thick about half of the ventral thickness, with gentle median fold. Ornaments made by angular costae on the flanks, 7–8 on each side. Sulcus and fold smooth. Shell punctate.

No serial sections were possible. On a fragmentary specimen, the median septum and the two long divergent dental lamellae may be observed.

**Remarks.** – In the Anisian of Himalaya *Tulungospirifer*



**Table 1.** Dimensions (in mm) of the *Nudirostralina mutabilis* (Stoliczka, 1866).

Specimen	Length	Width	Thickness	Costae ratio
RMA62	12.9	12.9	7.7	2/3; 3/2
RMA 65	12.7	13.4 deformed	9.2	2/3; 3/2
RMA 89/1	> 12.0	11.9	9.4	2/3; 3/2
RMA 89/2	12.9	12.7	9.2	1/2; 2/1
RMA89/3	13.2	12.6	9.6	2/3; 3/2
RMA 89/4	14.2	13.6	9.7	2/3; 3/2
RMA 89/5	13.4	14.8	10.7	2/3; 3/2

*stracheyi* (Salter, 1865) has shape with extended mucronate hinge and coarser costae. *Punctospirella fragilis* (Schlotheim, 1813) has slightly coarser ribs, usually in number of five on each side, and with more curved interarea. *Lepismatina lilangensis* has non-mucronate shape and slightly thinner costae, up to seven on each flank. The dental lamellae are attached together at mid length, and are not discrete as in *Punctospirella*. *Lepismatina manca* (Bittner, 1890) has different internal dental lamellae.

**Occurrence.** – Socotra, brachiopod assemblages 2 and 3. Lalung (Lilang) in Spiti, Western Himalaya (Bittner, 1899). Top of the Himalayan Muschelkalk at Muth (Spiti, Bed E37) (Krystyn *et al.* 2004). Bithynian/Pelsonian in Spiti, Illyrian in Socotra.

Order Athyridida Boucot, Johnson & Staton, 1964  
 Suborder Athyrididina Boucot, Johnson & Staton, 1964  
 Superfamily Athyridoidea Davidson, 1881  
 Family Diplospirellidae Schuchert, 1894  
 Subfamily Ochotathyridinae Alvarez, Rong & Boucot, 1998

### Genus *Spirigerellina* Dagys, 1974

**Type species.** – *Spirigerellina pygmaea* Dagys, 1974. Olenekian of Mangyshlak, Kazakstan.

### *Spirigerellina stoliczkai* (Bittner, 1899)

Figures 7A–I, 8, 9, 10.

- 1898 *Spirigera (Athyris) Stoliczkai* Bittner, p. 691. [*nomen nudum*]  
 1899 *Spirigera (Athyris) Stoliczkai* Bittner 1899, p. 23, pl. 3, figs 1–17.  
 1907 *Spirigera Stoliczkai* Bittner, 1899. – Diener, p. 3.  
 non 1928 *Spirigera stoliczkai* Bittner, 1899. – Parona, p. 21, pl. 2, figs 6, 7.  
 non 1928 *Spirigera stoliczkai* var. *prehunica* Bittner, 1899. – Parona, p. 21, pl. 2, fig. 8.

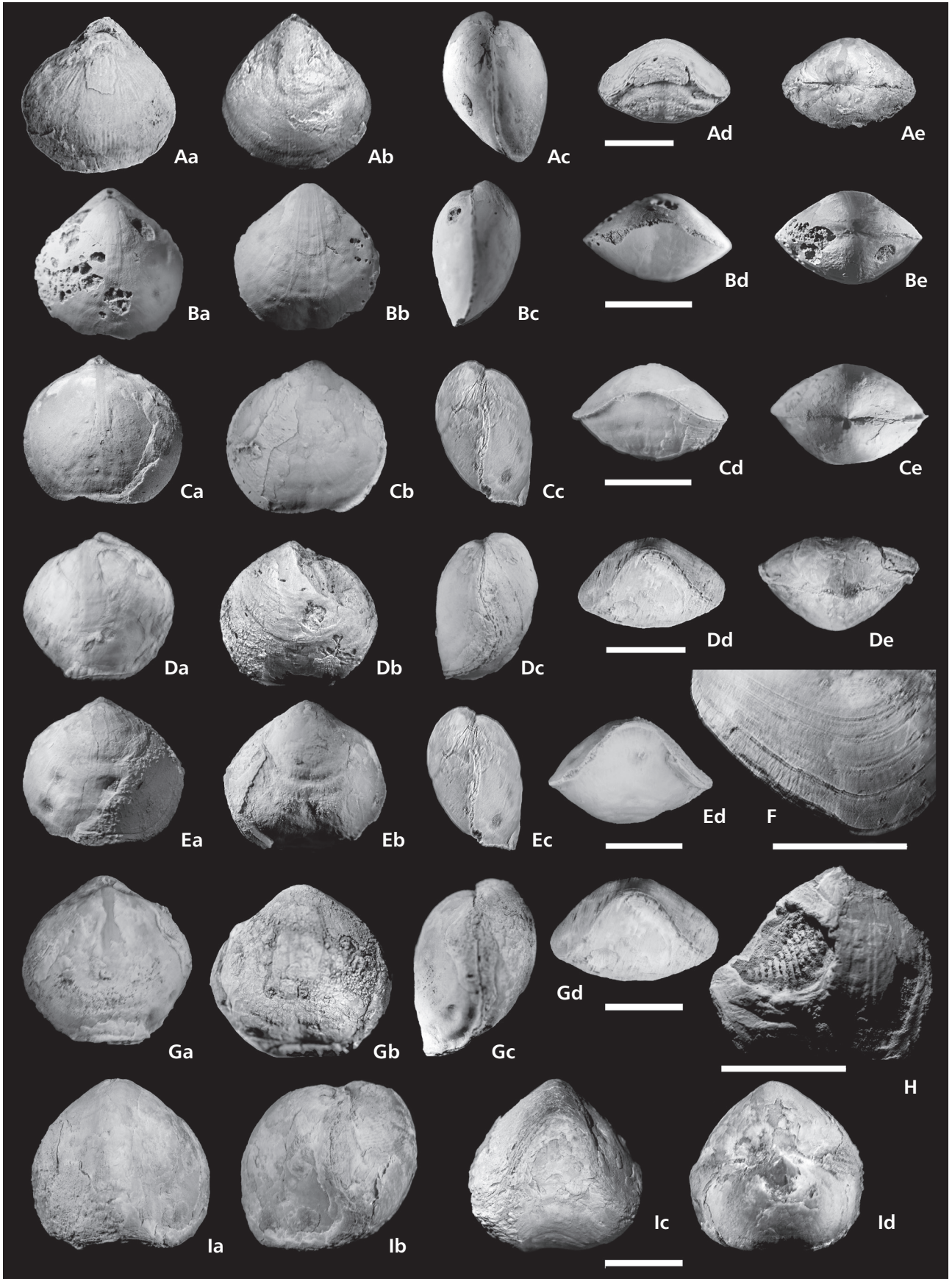
1975 *Spirigerellina stoliczkai* Bittner, 1899. – Siblik, p. 145, figs 6, 7; pl. 21, figs 1–3.

**Material.** – Socotra Island: about 370 specimens. MPUM 11538, RM17 top (= RMA60) (41 spec.); MPUM11539, RM41 (7 spec.); MPUM11540, RMA58 (5 spec.); MPUM11541, RMA60 (10 sp.); MPUM11542, RMA61 (31 spec.); MPUM11543, RMA61/62 (96 spec.); MPUM11544, RMA 62 (26 spec.); MPUM11545, RMA64 (5 spec.); MPUM11546, RMA65 (65 spec.); MPUM11547, RMA68 (29 spec.); MPUM11 548, RMA89 (58 spec.). Specimens are usually articulated, only in RMA89 some is distorted and disarticulated. Muth, Spiti, Western Himalaya: MPUM11549, E37 (3 specimens).

**Description.** – Smooth biconvex shell, subpentagonal in outline, with width usually larger than length. The height rapidly increases with size; the gerontic specimens have a bump in the dorsal valve towards the front in lateral view. Strongly uniplicate, with fold and sulcus well defined but not sharply delimited and visible since half to  $\frac{2}{3}$ rd of the length. Cardinal hinge gently curved. Foramen closed by deltidial plates towards the hinge in permesothyrud position. Dorsal muscle field with median adductors very narrow and elongated, gently subdivided by the myophragm, and larger but shorter external adductors. Diductors reaching half of the length of the valve in the ventral valve (Fig. 7Bb). Mantle channels rectilinear and well separated (Fig. 7Aa).

Growing lamellae visible only on well-preserved specimens. Fine radial striae, about 18–20 on 5 mm at the front, on slightly decorticated specimens (Fig. 7F). Shell impunctated. Scatter plots of length vs width and thickness vs width are reported in Fig. 8.

**Internal features:** Ventral valve with subparallel dental lamellae, vertically extending from the flank of the delthyrium for about the  $\frac{1}{8}$  of the length. Delthyrial cavity subquadrate. Lateral cavities open. Teeth simple, not crenulated, inserted in the sockets with low angle. Small and short denticula.



Dorsal valve with very strong cardinal process and thick hinge plate, ending laterally in two wings that form the inner socket ridges. Outer socket ridges poorly developed, almost flat. Posterior open coelomic cavity, with no septum; only a gentle myophragm visible forward.

Crural basis gently inclined towards the centre of the cavity. The spiralia were always broken in the four specimens sectioned from Socotra, while the specimen from Spiti is heavy recrystallized. Spiralia with at least eleven volutions in a decorticated specimen (Fig. 7H).

**Remarks.** – The shape and the internal features match well with definition of the genus *Spirigerellina* Dagys, 1974. On the other hand, there are differences with the serial sections of Siblik (1975), because our sectioned specimens do not have the median septum in the dorsal valve and have instead open posterior coelomic cavity. The sectioned specimen E37/2 from Muth, seems to have the coelomic cavity open, as it was reported in Bittner (1899, pl. 2, fig. 9). The recrystallization, however, prevents a more accurate investigation.

**Occurrence.** – *Spirigerellina stoliczkai* is very frequent in Socotra, brachiopod assemblages 2 and 3. It is known through Western and Central Himalaya, from Spiti (Rimkin Fm., Himalayan Muschelkalk Mb. to Rimki-Pajar (Kumaon), and Dolpo (Mukut Lmst.) in Nepal. The Karakorum Pass occurrence (Parona 1928) is not correct, after checking (MG) of the material stored in the Florence Museum. Dagys (1974) reports this species also from Primorye. The age is Illyrian to earliest Ladinian in Socotra, Bithynian to Pelsonian in Himalaya.

Order Terebratulida Waagen, 1883

Suborder Terebratulidina Waagen, 1883

Superfamily Dielasmatoidea Schuchert, 1913

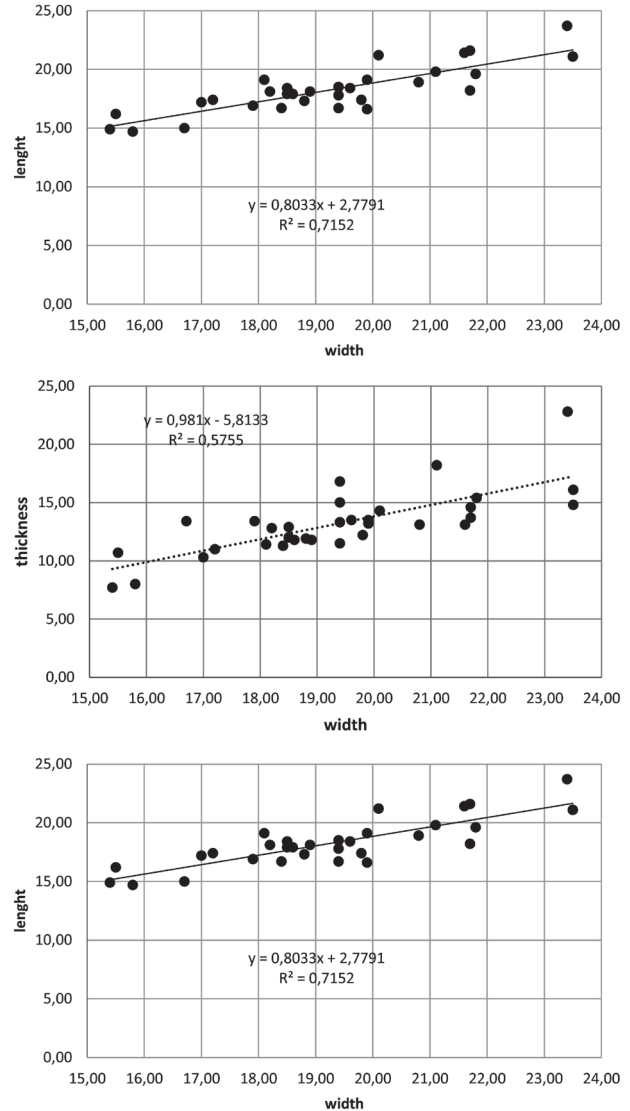
Family Dielasmatidae Schuchert, 1913

### Genus *Dielasma* King, 1859

**Type species.** – *Terebratulites elongatus* Schlotheim, 1816. Upper Permian of Thuringia, Germany.

### “*Dielasma*” *himalayanum* Bittner, 1899

Figures 11A, B, 12



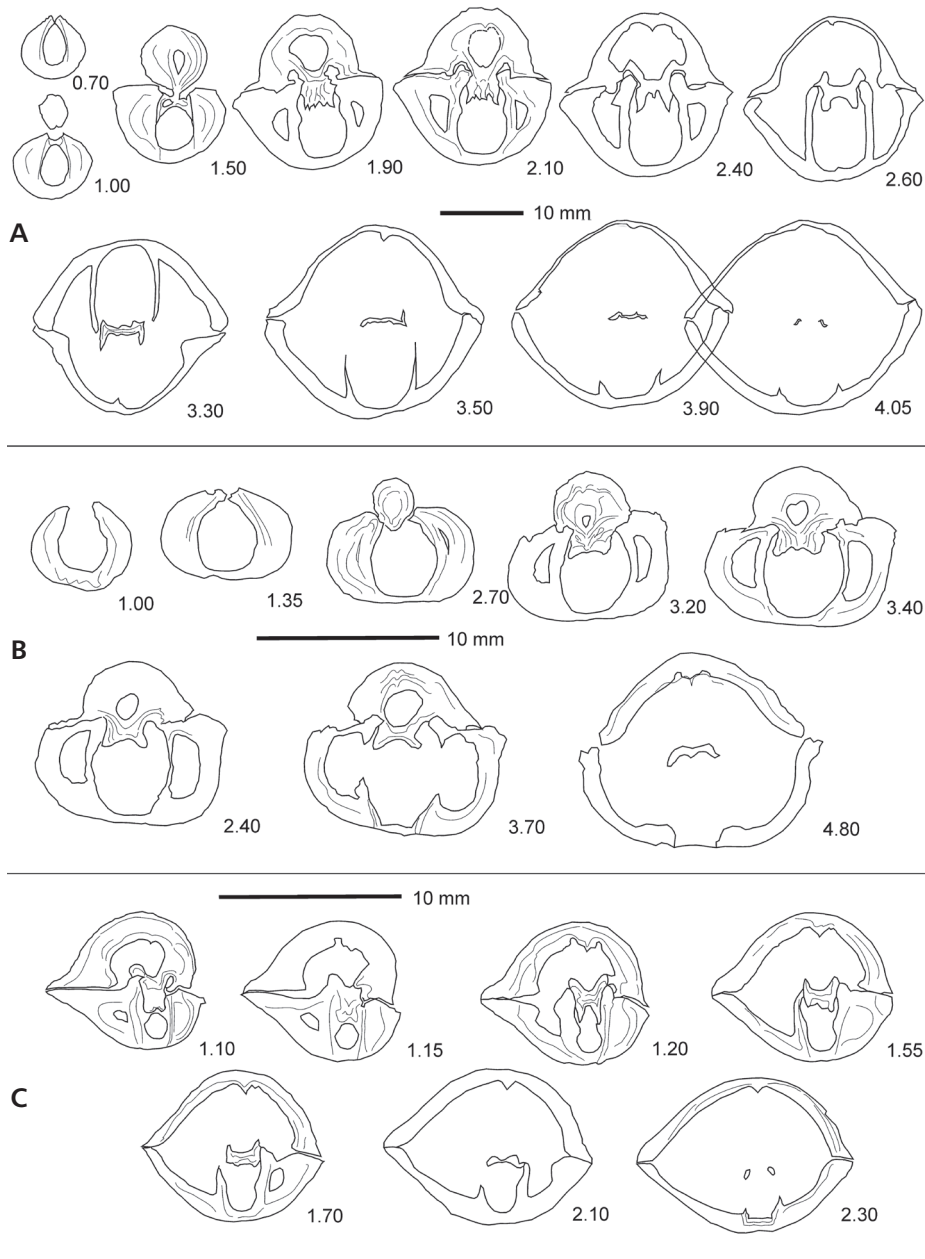
**Figure 8.** Scatter diagram of 34 specimens of *Spirigerellina stoliczkai* (Bittner, 1899) with length vs. width and thickness vs. width.

1899 *Terebratula* (*Dielasma*) *himalayanum* Bittner, p. 25, pl. 5, figs 1–8, 10, 11.

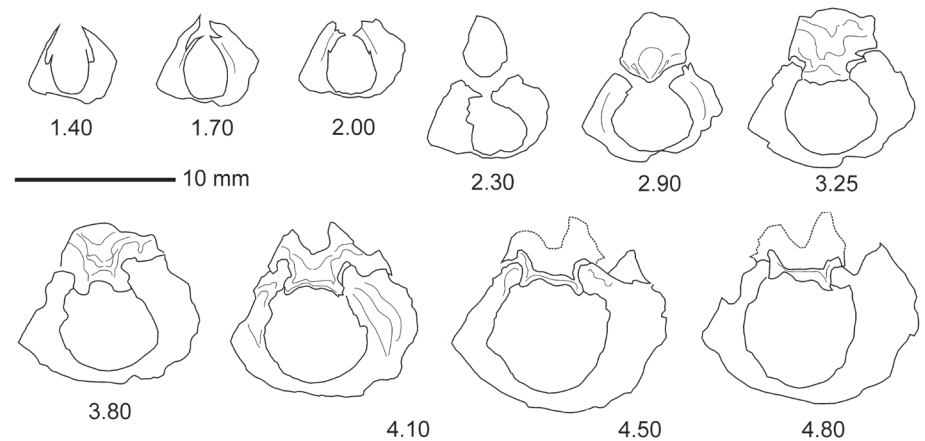
1975 *Dielasma himalayanum* Bittner, 1899. – Siblik, p. 135, pl. 19, figs 1, 3; text-figs 1a, 1b, 2.

1976 “*Adygella*” *himalayana* Bittner, 1899. – Jin & Sun in Jin et al., p. 325, pl. 8, figs 29–32, text-fig. 26.

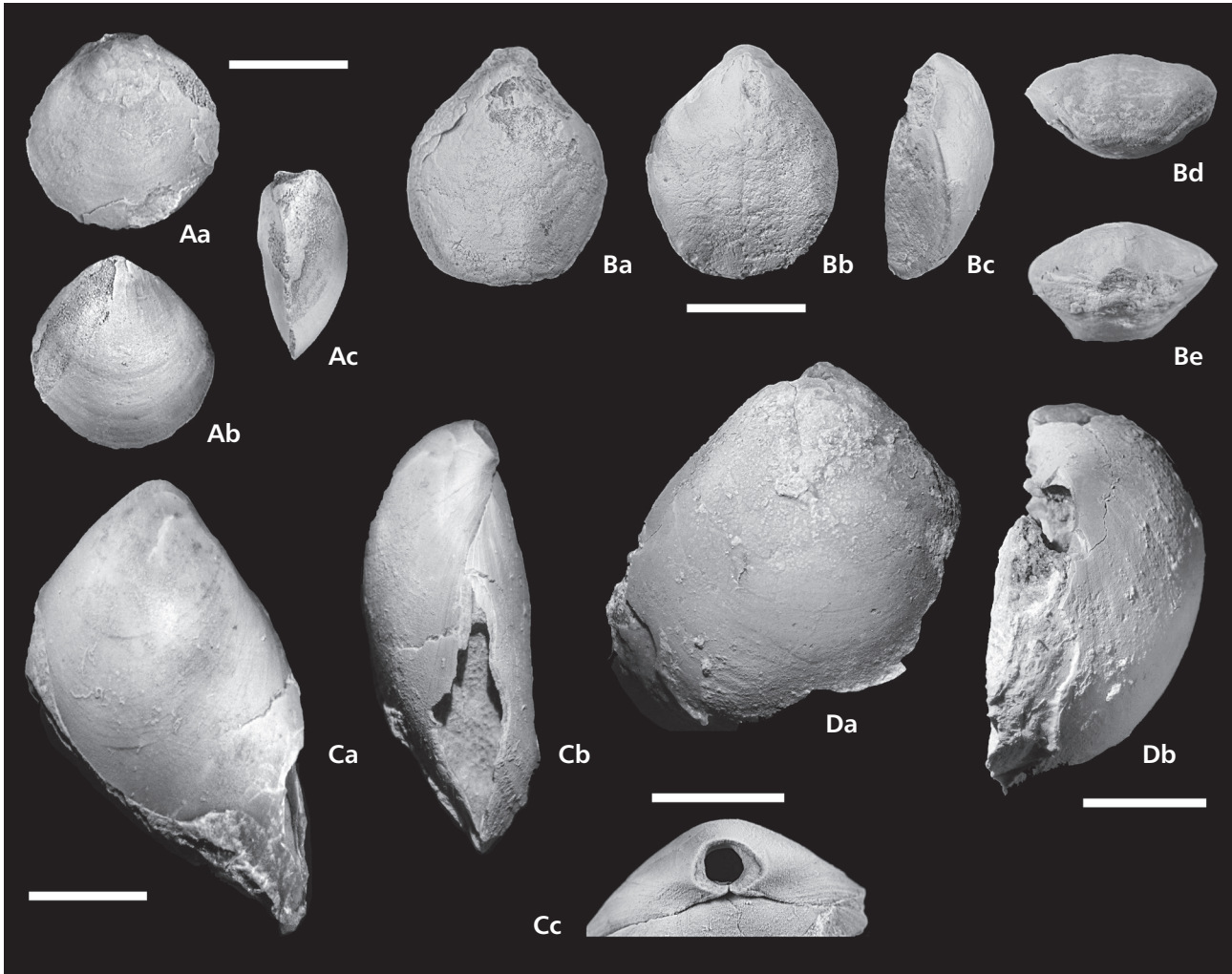
**Figure 7.** *Spirigerellina stoliczkai* (Bittner, 1899). Scale bar = 1 cm; Aa–e – dorsal, ventral, lateral, anterior, and posterior views, respectively. Specimen E 37/1, MPUM11549. Muth (Spiti, India); Ba–e – dorsal, ventral, lateral, anterior, and posterior views, respectively. Specimen RMA 61/62/6. MPUM 11543; Ca–e – dorsal, ventral, lateral, anterior, and posterior views, respectively. Specimen RMA 62/3. MPUM 11544; Da–e – dorsal, ventral, lateral, anterior, and posterior views, respectively. Specimen RMA 89/10. MPUM11548; Ea–e – dorsal, ventral, lateral, and anterior views, respectively. Specimen RMA 62/1. MPUM 11544; F – detail of the external surface with growing lamellae and faint capillae. Specimen RMA61/62/13, MPUM11544; Ga–e – dorsal, ventral, lateral, and anterior views, respectively. Specimen RMA 61/62/12. MPUM 11543; H – spirallium seen from the ventral valve side. Specimen RM17/41, MPUM 11538; Ia–e – dorsal, lateral, anterior, and posterior views, respectively. Specimen RMA 58/1. MPUM 11540.



**Figure 9.** *Spirigerellina stoliczkai* (Bittner, 1899). Serial sections. Distance from the umbo in mm. Scale bar = 1 cm; A – specimen RMA 68/1, MPUM 11547; B – specimen RMA 61/62/17, MPUM 11543; C – Specimen RMA 61/62/18, MPUM 11543.



**Figure 10.** *Spirigerellina stoliczkai* (Bittner, 1899). Serial sections. Distance from the umbo in mm. Scale bar = 1 cm. Specimen E 37/2; MPUM 11549, Muth (Spiti, India).



**Figure 11.** A, B – “*Dielasma*” *himalayunum* Bittner, 1899. Scale bar = 1 cm; Aa–c – dorsal, ventral, and lateral, views, respectively. Specimen E 37/2. MPUM 11551; Ba–e – dorsal, ventral, lateral, frontal, and posterior view. Specimen Tulong/1, MPUM 11588. • C, D – Dielasmatid gen. et sp. ind.; Ca–c – ventral and lateral views, and detail of the foramen. Specimen 89/20; MPUM 11556; Da, b – ventral and lateral views. Specimen 85bis, MPUM 11555.

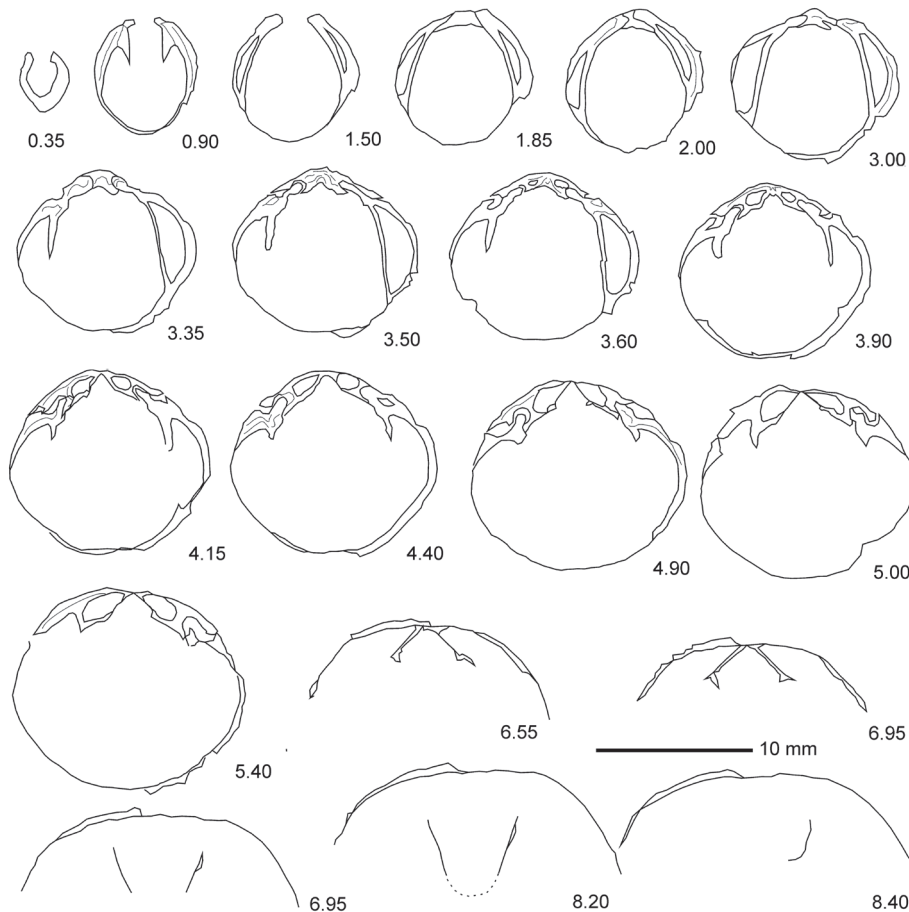
**Material.** – Muth, Spiti, India (MPUM 11551, E37 – 2 specimens). Tulong, South Tibet MPUM 11588 (3 specimens).

**Remarks.** – Due to the scarcity of the material, this species cannot be fully discussed. Some note may be added about the structure of the cardinalia, already described by Siblík (1975). There is a short pedicle collar. The dental plates are posteriorly very near to the valve wall, then almost vertical. The long teeth are obliquely inserted in the sockets, not crenulated, but with developed denticula. The inner hinge plates are directly inserted on the valve floor with no septalium. Strong inner socket ridges. Two high vertical blades, bearing crural process, possibly connected by a rounded band at the front, form the loop. Dimensions (in mm) of the “*Dielasma*” *himalayunum* Bittner, 1899 are listed in Table 2.

**Table 2.** Dimensions (in mm) of the “*Dielasma*” *himalayunum* Bittner, 1899.

Specimen	Length	Width	Thickness
E 37/1	> 16.50	16.60	7.50
E 37/2	25.60	–	12.50
Tulong/1	23.85	18.90	11.10
Tulong/2	21.70	18.80	14.50

As already pointed out by Bittner (1899), the cardinalia are different from *Coenothyris*, having septalium. The same holds true for *Adygella* (Siblík 1975). Cardinalia are very similar to *Dielasma*, a genus present in the Pennsylvanian to Permian. For this reason, the generic name is within inverted comers. Probably a new genus, but the material at disposal is not sufficient. *Tibetothyris* Jin & Sun, 1976 differs for the sulcuplicate to bisulcate shell.



**Figure 12.** “*Dielasma*” *himalayanum* Bittner, 1899. Serial sections. Distance from the umbo in mm. Scale bar = 1 cm. Specimen E 37/2, MPUM 11551, Muth (Spiti, India).

**Occurrence.** – “*Dielasma*” *himalayanum* was reported from the Tamba Kurkur Fm. in Zanskar (western Himalaya), from the Muschelkalk of Rimkin Payar and Rajhoti Pass (Central Himalaya), Lalung (Lilang) in Spiti (Bittner 1899) and from Dolpo (Nepal) (Siblík 1975). Our figured specimens are from the top of the Himalayan Muschelkalk at Muth (Spiti) and from the lower part of the Qudenggongba Fm. (Tulong, South Tibet), belonging to the Bithynian/Pelsonian in Himalaya.

**Genus *Adygella* Dagys, 1959**

**Type species.** – *Adygella cubanica* Dagys, 1959. Norian of Northwestern Caucasus, Russia.

***Adygella socotrana* sp. nov.**

Figures 13A–E, 14, 15

**Types.** – Holotype, specimen MPUM11552, RM23/3. Paratypes, the 60 specimens MPUM11553 from bed RM23.

**Type horizon and locality.** – *Adygella socotrana* assemblage, Ras Momi section.

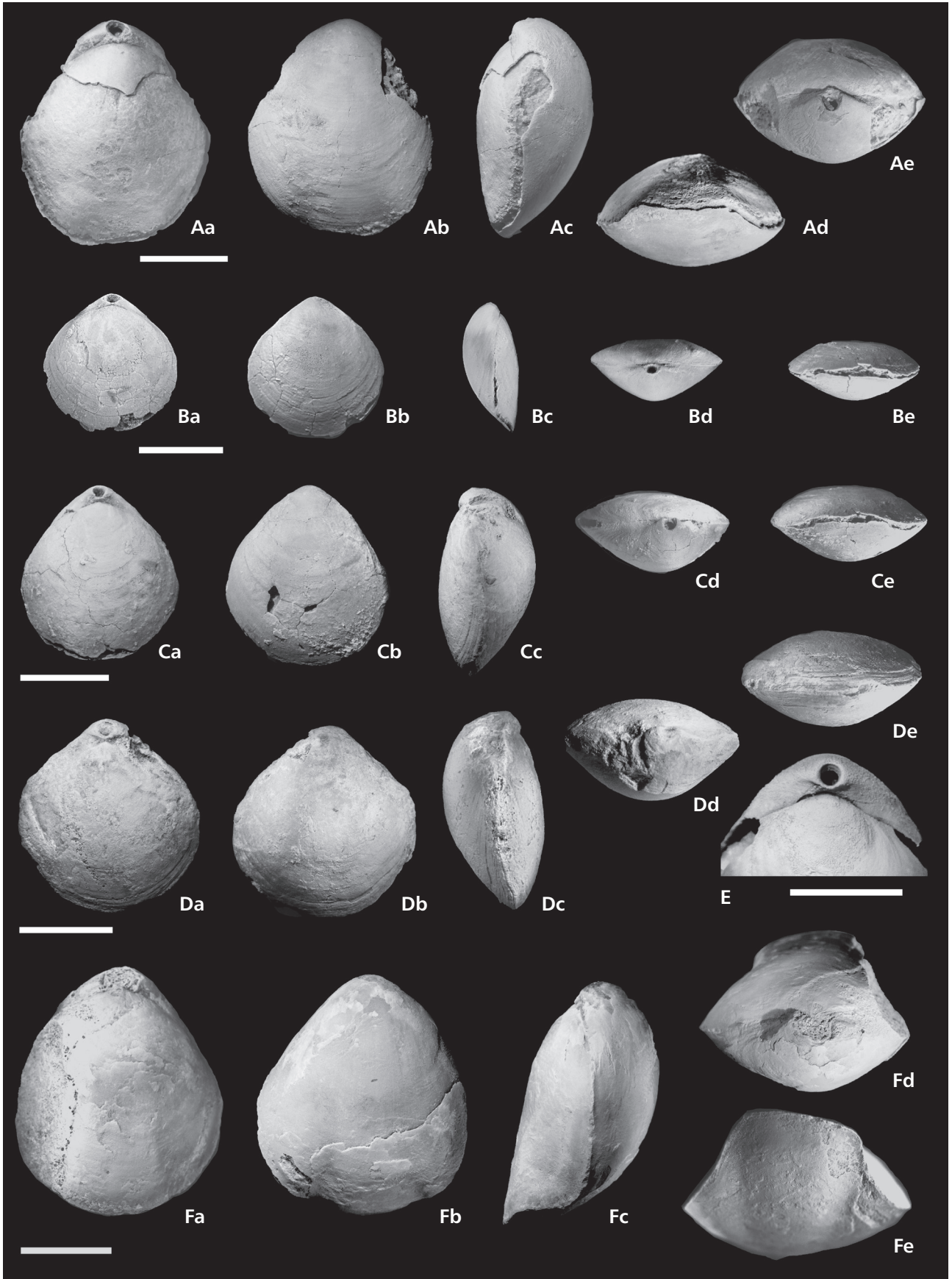
**Material.** – Socotra, Ras Momi section: MPUM11553, RM23 (61 spec.); MPUM 11554, RMA37 (7 spec.). Specimens are usually articulated.

**Etymology.** – From the island of Socotra.

**Diagnosis.** – Medium to large sized dielasmaticid, biconvex. Uniplicate in adult specimens, Smooth shell. Dental lamellae, septalium supported by short stout septum. No ventral septum.

**Description.** – Medium to large sized dielasmaticid,

**Figure 13.** *Adygella socotrana* sp. nov. Scale bar = 1 cm; Aa–e – dorsal, ventral, lateral, anterior, and posterior views, respectively. Holotype. Specimen RMA 23/2, MPUM 11552; Ba–e – dorsal, ventral, lateral, anterior, and posterior views, respectively. Paratype. Specimen RMA 23/1, MPUM 11553; Ca–e – dorsal, ventral, lateral, anterior, and posterior views, respectively. Paratype. Specimen RMA 23/2, MPUM 11553; Da–e – dorsal, ventral, lateral, anterior, and posterior views, respectively. Paratype. Specimen RMA 37/1, MPUM 11554; E – detail of the umbo, foramen with pedicle collar. Paratype. Specimen RMA 23/2, MPUM 11553; Fa–e – dorsal, ventral, lateral, anterior, and posterior views, respectively. Specimen RMA 37/3, MPUM 11554.



biconvex; length similar to the width in the juveniles, progressively longer. Anterior commissure rectilinear in the juveniles, uniplicate in the adults with fold and sulcus identified from the  $\frac{2}{3}$  of the length. Beak short with rounded ridges. Rounded, medium sized foramen at the apex of the beak. Shell smooth, with very faint growing lamellae. Endopunctuation visible. Most of the specimens are distorted or crashed because of the delicate shell (Table 3).

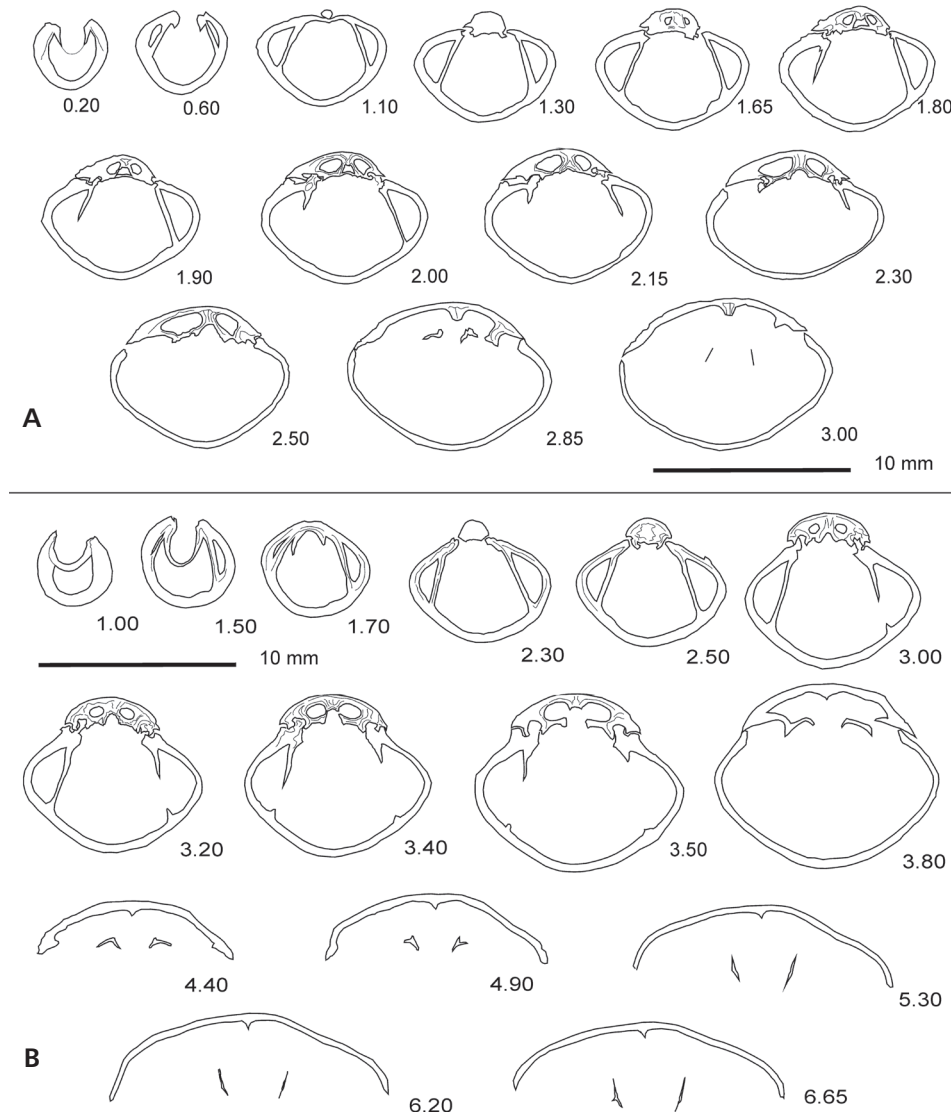
Internal characters: Dorsal valve with pedicle collar rounded and complete. Thin oblique dental lamellae, delimiting a trapezoidal delthyrial cavity. Teeth rounded and not crenulated, inserted obliquely in the sockets. External denticula well developed.

Ventral valve with inner hinge plates subhorizontal, fixed to a very low septalium supported by stout buttress. Hinge plates subhorizontal, short with high inner socket ridge. Figure 15 shows the internal structures of a larger

**Table 3.** Dimensions (in mm) of the *Adygella socotrana* sp. nov.

Specimen	Length	Width	Thickness
RM 23/1	16.5	15.9	8.6
RM 23/2	19.9	18.1	9.0
RM 23/3	25.3	22.2	–
RMA 37/1	21.6	20.6	11.7
RMA 37/2	21.9	16.1	10.4
RMA 37/3	26.9	23.5	16.3
RMA 89	14.8	12.9	8.7

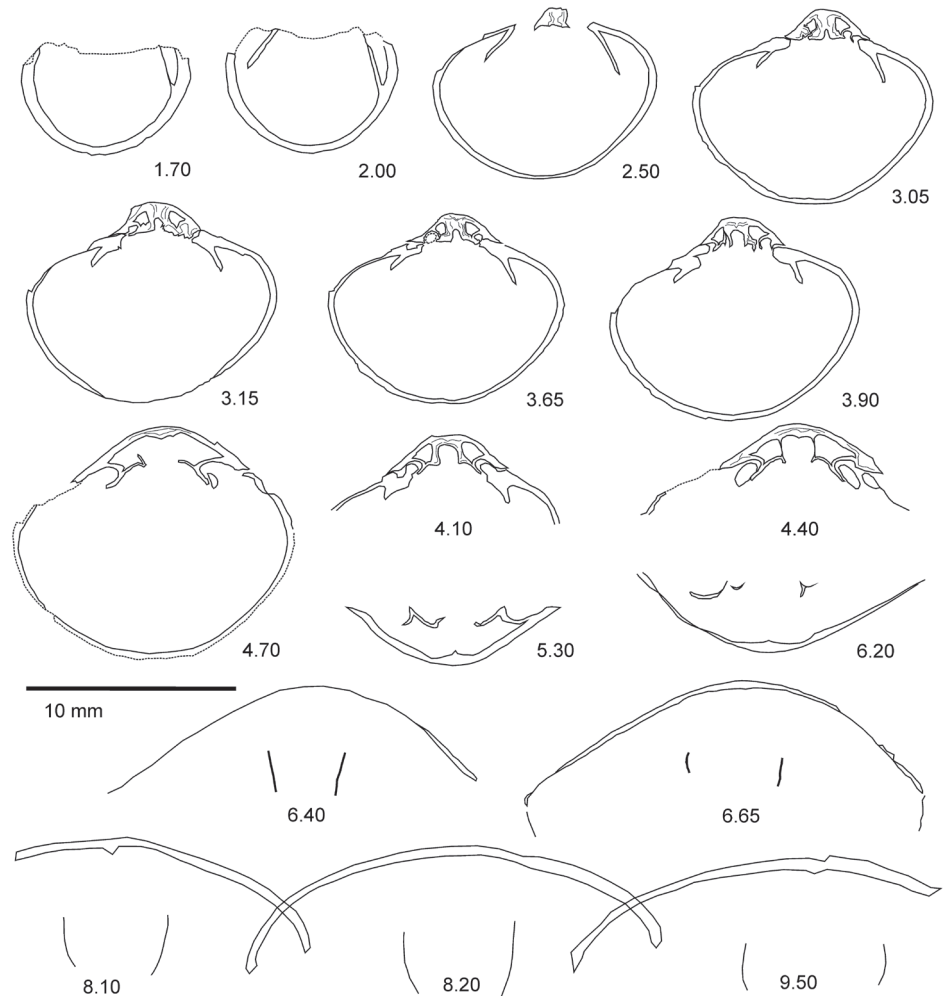
specimen, where the inner hinge plates are nearly fixed to the wall, with almost no septalium. We interpret the feature as linked to the size and to the angle of cutting of the section. Crura developed to form a vertical lamina. Loop not preserved.



**Figure 14.** *Adygella socotrana* sp. nov. Serial sections. Distance from the umbo in mm. Scale bar = 1 cm; A – specimen RM 23/a, MPUM 11553; B – specimen RM 23/b, MPUM11553.



**Figure 15.** *Adygella socotrana* sp. nov. Serial sections. Distance from the umbo in mm. Scale bar = 1 cm. Specimen RM37, MPUM11554.



*Remarks.* – *A. socotrana* differs from “*Dielasma*” *himalayanum* in the structure of dorsal cardinalia, bearing a septalium supported by a buttress. “*D.*” *himalayanum* instead, as already figured by Siblík (1975), has oblique thin inner hinge plates directly fixed to the valve floor, without septalium. In *A. cubanica*, type species of *Adygella*, the septalium is high, while in *A. socotrana* is short. This feature approaches *A. socotrana* to the genus *Coenothyris*, spread in the Middle Triassic. However, *Coenothyris* has well developed cardinal process and persistent long median septum in the ventral valve, absent in *A. socotrana*. *Adygella elongata* Yang & Xu, 1966 has higher septum supporting the septalium, as do *Adygella pentagonalis* Jin & Sun in Jin et al. (1976).

*Occurrence.* – *Adygella socotrana* sp. nov. is abundant in the lower brachiopod assemblage (RMA37, RM23). Bithynian age.

**Dielasmatid gen. et sp. ind.**

Figure 11C, D

*Material.* – Incomplete or fragmentary specimens, non-articulated ventral valves. MPUM 11587, RMA75bis (1 articulate spec.); MPUM11555, RMA85bis (2 spec.); MPUM 11556, RMA 89 (2 juvenile complete specimens and 4 fragments).

*Description.* – Large smooth dielasmatid, exceeding 35 mm both in length and in width. Ventral valve thicker than the dorsal. Foramen with developed pedicle collar.

*Remarks.* – The material at hand does not allow a complete identification and description. It is kept separate from *A. socotrana* because of its larger size, the higher angle at the shoulder. The age is different, Bithynian for *A. socotrana* vs. Early Ladinian for this species.

**Occurrence.** – Topmost part of the section, from 103 to m 106 (Fig. 2).

### Comparison between Socotra and Himalaya brachiopod faunas

The fauna of Socotra has strict counterparts in Himalaya, distributed along the ancient fringe of the Indian Plate during the Triassic, facing the Neo-Tethys Ocean (Gaetani & Garzanti 1991, Garzanti 1999, Sciunnach & Garzanti 2012). The overall Anisian marine succession of Himalaya is viewed as a persistent lateral developing marine succession, consisting of thin-bedded nodular limestone, often bundled together in massive beds that also form cliffs. These facies are replaced by bedded nodular limestones, with more erodible marly intercalations, around the Bithynian-Pelsonian boundary. Different formational names have been adopted, like Tamba Kurkur Fm. (Zanskar), Himalayan Muschelkalk (Spiti), and Qudenggongba Fm. (South Tibet). In general, they represent a progressive deepening of the Indian margin during the Anisian, resulting in a deep shelf environment, with low sedimentation rate and occasional hiatuses and condensations (Sciunnach & Garzanti 2012).

Brachiopods are always a minor component of the Anisian faunas of Himalaya. They were firstly collected and described at the beginning of the Himalayan reconnaissance of stratigraphy (Stoliczka 1866), and subsequently monographed by Bittner (1899) and Diener (1907) in Kashmir, Spiti, and Kumaon. Later, brachiopods were occasionally sampled and studied in Dolpo (Nepal) (Siblík 1975, Fuchs 1977), and with little sampling in Zanskar (Gaetani *et al.* 1986) and Spiti (India) (Krystyn *et al.* 2004). Chinese researchers performed further collection and taxonomy in South Tibet (Jin *et al.* 1976, Chen 1983, Yin 2003).

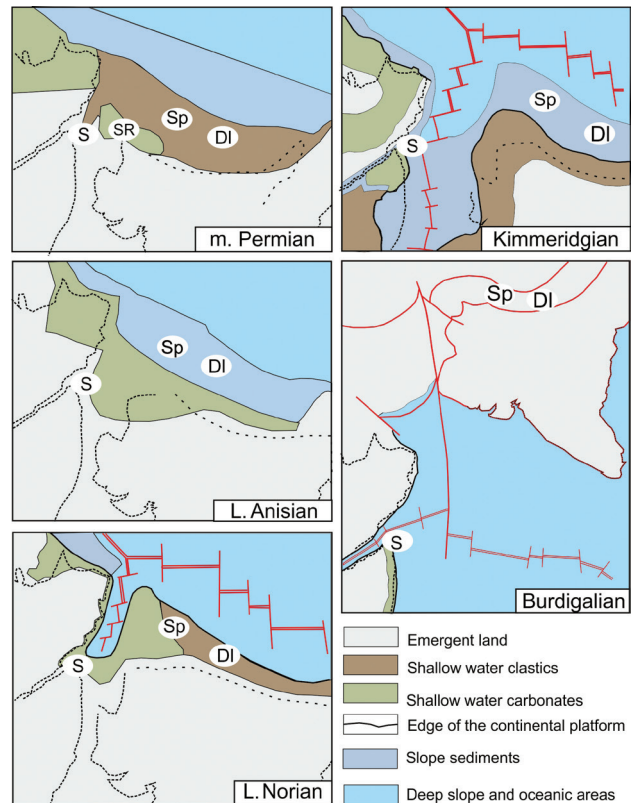
Although the brachiopod faunas of Himalaya and Socotra have some species in common, they lived in different environmental conditions. The Socotra brachiopods dwelled in shallow water, often under the influence of waves. Density of specimens is high to very high, and the diversity low. The Bithynian assemblage consists of a single species, *Adygella socotrana*, while the Illyrian is dominated by *Spirigerellina stoliczkai*, with minor occurrence of *Lepismatina lilangensis* and *Nudirostralina mutabilis*. Specimens may be coated by algal or bryozoans encrustations, and their internal structure is often broken, suggesting high-energy conditions. On the other hand, the Himalayan fauna, in Kashmir (Diener 1907), Zanskar (Gaetani *et al.* 1986), Spiti (Bittner 1899), and Dolpo (Siblík 1975), has higher diversity and lower density of the specimens. Brachiopods are not frequent and only slightly more abundant at the top of the Himalayan

Muschelkalk, where the lower sedimentation rate locally allowed a higher density of the buried specimens. This indicates an environment deeper than in Socotra, certainly below the storm wave base.

A difference between Himalaya and Socotra exists also in the time distribution of the brachiopods. In Himalaya the sea-bottom deepened quickly after the deposition of the Himalayan Muschelkalk and its lateral equivalents, making the environment less viable for brachiopods during the Late Anisian. In Socotra instead, the environment did not changed significantly, as it became just a bit richer in clay toward the upper part of the interval. Therefore, some brachiopod species could survive also during the Late Anisian.

### Socotra-Himalaya connection during the Middle Triassic

The affinity of the brachiopod fauna of Socotra with that of the Himalaya is a splendid example for a palaeobiogeographic analysis, as it allows an accurate reconstruction of the evolution of the southern Tethyan margin during the Triassic (Fig. 16).



**Figure 16.** Cartoons showing the palaeogeographic displacements suffered by the Triassic of Socotra (from Dercourt *et al.* 1993, simplified). Abbreviations: DI – Dolpo; S – Socotra; Sp – Spiti; Sr – Salt Range; St – South Tibet.

During the Paleozoic, the Afro-Arabian and the Indian plates were all merged in a single continental mass, which was part of the Gondwanaland. During the Permian, after the Gondwana glaciations, the sea transgressed onto the marginal areas of this supercontinent, as observed in Oman (Angiolini *et al.* 2003, Richoz *et al.* 2005) and in the present Himalaya (Gaetani *et al.* 1986, Archbold & Gaetani 1993; among others). The Neo-Tethys Ocean initiated its existence and started spreading, as shown by the repeated episodes of rifting detected in the marginal areas (Sciunnach & Garzanti 1996, 2012). These changes, however, are not recorded in Socotra, as it was still in a continental environment at that time. With the Triassic, the thermal cooling of the southern Tethyan margin increased its subsidence and reached fully open marine conditions along the future Himalayan margin (Garzanti *et al.* 1996, Garzanti 1999, Krystyn *et al.* 2004). Therefore, a marine ingressions was possible also at Socotra, as it formed the westward prosecution of the margin, where the first marine deposits are dated as early Olenekian. Other episodic transgressions occurred during the Anisian and the Early Ladinian forming shallow carbonate deposits, which continued until the Late Triassic, as testified by the bedded dolostone in the Ras Falanj area.

Between the end of the Triassic and the lowermost Jurassic, rifting occurred along the Oman-Somalia alignment, beginning the separation of Socotra from the Himalayan margin (Bosellini 1989). The opening of the North Somalian basin started with the M22 magnetic anomaly (150 Ma), inducing the split of the Madagascar-Seychelles-India block (Bosellini 1992, Marquer *et al.* 1998). The Indian Ocean began to open from the African-Arabian block, along a sinistral transform fault between Madagascar and the Seychelles (Patriat & Achache 1984, Schettino & Scotese 2005). This structure possibly extended along the eastern Oman margin, thus accommodating the rapid motion of India to the north, since the Chron 34 (83.5 Ma; Schettino & Scotese 2005). Consequently, the part of the continental margin including Socotra remained on the west side of the newly formed mid-oceanic ridge. Socotra laid near the present day Southern Oman, possibly along the Dofhar Mountains, with which it shares the crystalline basement (Lepvrier *et al.* 2002), and continued to stay attached to the Arabian Peninsula until the beginning of the Miocene (d'Acremont *et al.* 2005). When the Gulf of Aden started opening, Socotra separated from Oman and remained on the southern side of the oceanic ridge, loosely linked to the eastern African spur, the Somali Plateau (Fournier *et al.* 2007, Leroy *et al.* 2013). Since the late Eocene, the Gulf of Aden represents a good example of oblique rifting (Lepvrier *et al.* 2002, Leroy *et al.* 2013). Its activity increased during the early Miocene and continued until the present (Platel & Roger 1989, Leroy *et al.* 2013).

## Conclusions

The sedimentary succession of the Socotra Island testifies the occurrence of episodic marine ingressions along the southern Tethyan margin during the Early and Middle Triassic. Three distinct brachiopod assemblages are recognized within specific intervals of this succession, and have been dated by the co-occurring conodont assemblages as Bithynian, Illyrian, and Ladinian, respectively. Taphonomic features indicate that these brachiopods lived in a shallow water environment with high-energy.

The brachiopod fauna of Socotra is also compared with a few specimens from the Anisian of Spiti and South Tibet (Himalaya, India, and China), in order to verify a possible faunal affinity between Socotra and Himalaya. Despite the difference in the sedimentary environment, Socotra and Himalaya were connected during the Anisian, as both were part of the fringe of the Gondwanaland, facing the opening Neo-Tethys. As consequence of the repeated episodes of Gondwana splitting, Socotra remained attached to the African Plate, as the easternmost tip of the Somali Plateau. On the other hand, India drifted away, to eventually collide with the Asian margin during the Cenozoic and build the Himalayan mountain range.

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*Adygella socotrana* sp. nov. Gaetani, in Gaetani *et al.* has been registered in the ZooBank database: urn:lsid:zoobank.org:act:13D4EA88-C8F5-4F96-8CE6-8E87FB2281E9.

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